The Astrophysical Journal, 615:L69–L72, 2004 November 10

THE ULTRAVIOLET FLASH ACCOMPANYING GAMMA-RAY BURSTS FROM NEUTRON-RICH INTERNAL SHOCKS

Y. Z. Fan[1,2,3] and D. M. Wei[1,2]

Received 2004 July 27; accepted 2004 October 5; published 2004 October 14

ABSTRACT

In the neutron-rich internal shocks model for gamma-ray bursts (GRBs), the Lorentz factors (LFs) of ion shells are variable, and so are the LFs of accompanying neutron shells. For slow neutron shells with a typical LF of approximately tens, the typical β-decay radius reads $R_{\beta,s} \sim$ several $\times\ 10^{14}$ cm, which is much larger than the typical internal shocks radius $\sim 10^{13}$ cm, so their impact on the internal shocks may be unimportant. However, as GRBs last long enough [$T_{90} > 20(1+z)$ s], one earlier but slower ejected neutron shell will be swept successively by later ejected ion shells in the range $\sim 10^{13}$–10^{15} cm, where slow neutrons have decayed significantly. We show in this work that ion shells interacting with the β-decay products of slow neutron shells can power a UV flash bright to the 12th magnitude during the prompt gamma-ray emission phase or slightly delayed, which could be detected by the upcoming satellite *Swift* in the near future.

Subject headings: gamma rays: bursts — radiation mechanisms: nonthermal — shock waves

1. INTRODUCTION

As realized by many authors, the fireball of gamma-ray bursts (GRBs) may contain a significant neutron component in essentially all progenitor scenarios (e.g., Derishev et al. 1999a, 1999b; Beloborodov 2003a). The dynamics as well as the observable signatures (the neutrino emission from the proton-neutron decoupling and the changes in GRB light curves due to neutrons preceding the ion shell or catching up to it) of a relativistic neutron-rich fireball were first investigated by Derishev et al. (1999a, 1999b). Since then, many authors have focused their attention on the neutron-fed GRBs. If the neutron abundance is comparable to the proton abundance, the inelastic collision between differentially streaming protons and neutrons in the fireball will provide us observable 5–10 GeV neutrinos (Bahcall & Mészáros 2000, hereafter BM00; Mészáros & Rees 2000). The baryon-loading problem in GRB models can be ameliorated if a significant fraction of baryons confined in the fireball are converted to neutrons (Fuller et al. 2000). Further investigations of the implications for observations have been presented in Pruet & Dalal (2002, hereafter PD02) and Beloborodov (2003b, hereafter B03). In PD02, the short GRBs are assumed to be powered by external shocks, and the neutron component lags behind the ion component. As the ion ejecta have been decelerated significantly by the external medium, the decayed neutron ejecta catch up to the decelerated ion ejecta and powers keV emission. In B03, the neutron ejecta keep ahead of the ion ejecta. The β-decay ($n \rightarrow p + e^- + \bar{\nu}_e$) products share their momentum with the external medium immediately. As a result, the external medium is accelerated to a ultrarelativistic velocity. The interaction between the ion ejecta and the accelerated medium is very different from the usual case (i.e., a fireball ejecta interacting with the static medium). Therefore, the presence of neutron ejecta qualitatively changes the early dynamical evolution of the GRBs' remnant.

In PD02 and B03, only the "fast" neutron component has been taken into account. In fact, the long, complex GRBs are more likely to be powered by the interaction of shells with variant Lorentz factors (LFs), i.e., the internal shocks model (Paczyński & Xu 1994; Rees & Mészáros 1994). The best fit to the multiwavelength afterglows implies that a significant fraction of the initial kinetic energy has been converted into internal energy (Panaitescu & Kumar 2002), which requires that the difference in velocities between the shells is significant (i.e., the corresponding LFs satisfy $\eta_f \gg \eta_s$) and their masses are comparable ($m_f \approx m_s$; Piran 1999, hereafter P99). (Throughout this work, the subscript f, s represent the fast/slow shells, respectively; n, p represent the neutron/proton components, respectively.) Typically, η_s is on the order of tens and η_f is on the order of hundreds. Thus, for the slow shell, the n, p components coast with $\Gamma_{n,s} = \Gamma_{p,s} \simeq \eta_s$ since $\eta_s < \eta_\pi \simeq 3.9 \times 10^2 L_{52}^{1/4} r_{0,7}^{-1/4} [(1+\xi)/2]^{-1/4}$ (BM00), where L is the total luminosity of the ejecta, r_0 is the radius of the central engine, and ξ is the ratio of the neutrons to the protons contained in the shells. In this Letter, we adopt the convention $Q_x = Q/10^x$ for expressing the physical parameters, using cgs units. For the fast shell, the n, p components move with different LFs: $\Gamma_{n,f} < \Gamma_{p,f}$, since generally $\eta_f > \eta_\pi$ (BM00). In the internal shocks phase, the fast ion shell catches the slower but earlier one at a radius $R_{\rm int} \sim 10^{13}$ cm and forms a new shell moving with an LF $\Gamma_m \sim$ several hundred (hereafter the "new" formed shell is called the "i-shell"). At $R_{\rm int}$, the β-decay of the neutron component is unimportant unless the typical variability timescale is longer than 0.1 s (see Rossi et al. 2004 for more information).

As the duration of GRBs grows long enough, the much later ejected i-shell catches up to the earlier slow neutron shell (hereafter the "n-shell") at $R_{\rm cat} \approx 2\Gamma_{n,s}^2 c\delta T/(1+z)$, where δT is the ejection time-lag of the earlier slow n-shell and the later i-shell. On the other hand, the β-decay radius of slow neutrons reads $R_{\beta,s} \approx 2.6 \times 10^{13} \Gamma_{n,s}$ cm, at which slow neutrons have decayed significantly. As long as $R_{\rm cat}$ is comparable with $R_{\beta,s}$, i.e., $\delta T \geq 14(1+z)\Gamma_{n,s,1.5}^{-1}$, the decayed products of earlier but slower ejected neutron shells will be swept orderly by the later ejected ion shells in a range $\simeq R_{\rm int}$–$R_{\beta,s}$. The possible emission signature powered by that interaction is of our interest in this Letter. Otherwise, for GRBs much shorter than $14(1+z)\Gamma_{n,s,1.5}^{-1}$ s, the last i-shell crosses the first slow n-shell at a radius $\ll R_{\beta,s}$, where the β-decay is unimportant and there is no observable signature.

[1] Purple Mountain Observatory, Chinese Academy of Science, 2 West Beijing Street, Nanjing 210008, China.
[2] National Astronomical Observatories, Chinese Academy of Sciences, A20 Datun Road, Chaoyang Beijing 100012, China.
[3] On leave at the Department of Physics, University of Nevada, Las Vegas, NV 89154; yzfan@pmo.ac.cn (yzfan@physics.unlv.edu), dmwei@pmo.ac.cn.

2. THE SIMPLEST MODEL

Even for a neutron-free internal shocks model, so far the practical LF distribution of shells involved is far from clear, let alone, say, the neutron-rich one. Here we use an approximate model proposed by Guetta et al. (2001), in which the LFs of i-shells are drawn from a bimodal distribution, $\Gamma_{\rm ej} = \eta_f$ or $\Gamma_{\rm ej} = \eta_s$, with equal probability. That simple model is favored by its relative high-energy conversion efficiency and peak energy. In this Letter, mainly for simplicity, we make the following assumptions: (1) $\xi = 1$, and the ratios between the mass of the fast neutrons, slow neutrons, and i-shells are 1 : 1 : 2. (2) Each fast (slow) neutron/ion shell moves with the same LF $\Gamma_{n,f} \sim 300$ ($\Gamma_{n,s} \sim 30$) and $\Gamma_{p,f} \sim 1000$ ($\Gamma_{p,s} \sim 30$), respectively. After the merger of a pair of fast/slow ion shells, the resulting i-shell moves with $\Gamma_m \sim 200$. (3) The energetic ejecta are expanding into the low-density interstellar medium (ISM), which is the case for most GRBs (Panaitescu & Kumar 2002). (4) The duration of the GRB is longer than $30(1+z)$ s, since the constraint $\delta T \simeq 14(1+z)\Gamma_{n,s,1.5}^{-1}$ s should be satisfied.

The β-decay radius of fast neutrons $R_{\beta,f} \approx 8 \times 10^{15}\Gamma_{n,f,2.5}$ cm is much larger than $R_{\beta,s}$. We ignore them since for $R \leq R_{\beta,s}$, there is only a small fraction of fast neutrons decayed. The ISM has been swept by the early and fast ions as well as the decayed products of fast neutrons, so the decay products of slow neutrons move freely.

We assume that at radius R, the $(k-1)$th i-shell crosses the jth slow n-shell ($j, k \gg 1$). At radius $\simeq R + \Delta R$, the kth i-shell will catch up with the jth slow n-shell, where $\Delta R \approx 2\Gamma_{n,s}^2\Delta$, $\Delta \approx c\delta t/(1+z)$, and $\delta t \sim 0.01(1+z)$ s is the typical variability timescale of GRBs. For the jth n-shell, the products of slow neutrons decayed at radius $\leq R$ have been carried away by i-shells ejected earlier than the kth one. Hence the mass swept by the kth i-shell is $\Delta M \simeq (M_n \Delta R)/R_{\beta,s}$, where $M_n \equiv M_n^0 \exp(-R/R_{\beta,s})$, M_n^0 being the initial rest mass of the n-shell. Thus, the averaged comoving number density of protons (due to β-decay) swept by the kth i-shell can be estimated by

$$n \approx \frac{\Delta M}{4\pi R^2 m_p \Gamma_{n,s}\Delta} \approx \frac{\Gamma_{n,s}M_n}{2\pi R^2 m_p R_{\beta,s}}. \quad (1)$$

Note that in front of the much later ejected i-shells, there are hundreds of decaying n-shells. With the assumptions made above, the whole process of each i-shell interacting with these decaying n-shells is rather similar. For convenience, in our treatment below, the discrete interaction of each i-shell with these decaying n-shells has been simplified as an i-shell sweeping a moving proton trail (the LF of which is $\Gamma_{n,s}$) with a continuous number density n. The dynamics of that interaction can be described by the shock model as follows. Now that the trail is moving with an LF $\Gamma_{n,s} \sim$ tens, the generated thermal energy (comoving frame) in the shock front satisfies $dU = (\gamma_{\rm rel} - 1)dmc^2$ (e.g., B03) rather than $dU = (\gamma - 1)dmc^2$, where $\gamma_{\rm rel} = \gamma\Gamma_{n,s}(1 - \beta_\gamma\beta_{\Gamma_{n,s}})$ is the LF of the decelerating i-shell (the LF of which is γ) relative to the trail; β_γ and $\beta_{\Gamma_{n,s}}$ are the corresponding velocity of γ and $\Gamma_{n,s}$; and the mass swept by the i-shell reads

$$dm = 4\pi n m_p \Gamma_{n,s} R^2(\beta_\gamma - \beta_{\Gamma_{n,s}})dR \simeq \frac{M_n}{R_{\beta,s}}dR. \quad (2)$$

After some simple algebra, the energy conservation of the system (the decelerating i-shell and the swept slow neutron trail) yields

$$\frac{d\gamma}{dm} = -\frac{\gamma\gamma_{\rm rel} - \Gamma_{n,s}}{M_{\rm ion} + m + (1-\epsilon)U}, \quad (3)$$

where $M_{\rm ion}$ is the rest mass of the i-shell and ϵ is the radiation efficiency of the shock. For $\Gamma_{n,s} = 1$, equation (3) reduces to the familiar form $d\gamma/dm = -(\gamma^2 - 1)/[M_{\rm ion} + m + (1-\epsilon)U]$ (P99).

In the downstream, the electrons have been heated by the shock. As usual (e.g., P99), we assume that the shocked electrons distribute as $(dn/d\gamma_e) \propto \gamma_e^{-p'}$ for $\gamma_e > \gamma_{e,m}$, where $p' \sim 2.3$ is the typical power-law index, $\gamma_{e,m} \approx \epsilon_e[(p'-2)/(p'-1)](m_p/m_e)(\gamma_{\rm rel} - 1)$; and ϵ_e and ϵ_B are the fractions of the shock energy given to electrons and the random magnetic field at shock, respectively. The comoving downstream magnetic field $B \approx [32\pi\epsilon_B\gamma_{\rm rel}(\gamma_{\rm rel} - 1)nm_pc^2]^{1/2}$. As shown in P99, there is a critical LF above which synchrotron radiation is significant: $\gamma_{e,c} = [6\pi m_e c/(1+Y)\sigma_{\rm T}\gamma B^2 t]$, where $t = t_{\rm obs}/(1+z)$ is determined by $dR = 2\gamma^2 c dt$ ($t_{\rm obs}$ being the observer time, $z \sim 1$ being the redshift of GRBs); $\sigma_{\rm T}$ is the Thomson cross section; and Y is the Compton parameter (e.g., Wei & Lu 1998, 2000; Sari & Esin 2001): $Y \simeq -[1 + (1 + 4x\epsilon_e/\epsilon_B)^{1/2}]/2$, where x is the radiation coefficient of electrons, so $\epsilon \equiv x\epsilon_e$. For $\gamma_{e,m} > \gamma_{e,c}$ (fast cooling), $x = 1$. For $\gamma_{e,m} < \gamma_{e,c}$, $x = (\gamma_{e,m}/\gamma_{e,c})^{(p'-2)/2}$ (slow cooling).

Given a proper boundary condition, equation (3) can be easily solved. With the resulting $\gamma_{e,m}$, $\gamma_{e,c}$, and B, we can calculate the typical synchrotron radiation frequency $\nu_m = (\gamma_{e,m}^2\gamma eB)/[2(1+z)\pi m_e c]$ (e being the charge of electron), the cooling frequency $\nu_c = (\gamma_{e,c}^2\gamma eB)/[2(1+z)\pi m_e c]$, and the self-absorption frequency ν_a (the detailed calculation of ν_a can be found in the appendix of Wu et al. 2003), with which we can analytically calculate the synchrotron radiation flux at the fixed band. The numerical results for these typical frequencies have been plotted in Figure 1, where the parameters are taken as $M_{\rm ion} = 2M_n^0 = 5.6 \times 10^{26}$ g, which corresponds to a luminosity $L = 10^{52}$ ergs s^{-1}, and $\delta t = 10^{-2}(1+z)$ s, $\Gamma_m = 200$, $\Gamma_{n,s} = 30$, $\epsilon_e = 0.3$, $\epsilon_B = 0.01$, and $z = 1$ ($D_L = 2.2 \times 10^{28}$ cm). As shown in Figure 1, at the early time the electrons are usually in the fast cooling case and ν_a is above the optical band. Finally, the electrons are in the slow cooling case and ν_a drops to approximately a few $\times\ 10^{13}$ Hz. (Currently, the observed emission is coming from hundreds of i-shells interacting with the slow neutrons trail. For the same reason, in our estimating the self-absorption frequency, the total number of electrons contributed has been assumed to be 300 times that of one trail. In fact, if just an i-shell interacting with the slow neutron trail has been taken into account, ν_a should be 1 order or more less than the value presented here.)

The synchrotron flux as a function of observer frequency can be approximated as follows. In the case of fast cooling (just for $\nu_a > \min\{\nu_c, \nu_m\}$; for $\nu_a < \min\{\nu_c, \nu_m\}$, please refer to eqs. [4]–[5] of Zhang & Mészáros 2004),

$$F_\nu \approx F_{\rm max}\begin{cases}(\nu_c/\nu_a)^3(\nu/\nu_c)^2, & \nu < \nu_c,\\ (\nu_a/\nu_c)^{-1/2}(\nu/\nu_a)^{5/2}, & \nu_c < \nu < \nu_a,\\ (\nu/\nu_c)^{-1/2}, & \nu_a < \nu < \nu_m,\\ (\nu_m/\nu_c)^{-1/2}(\nu/\nu_m)^{-p'/2}, & \nu > \nu_m.\end{cases} \quad (4)$$

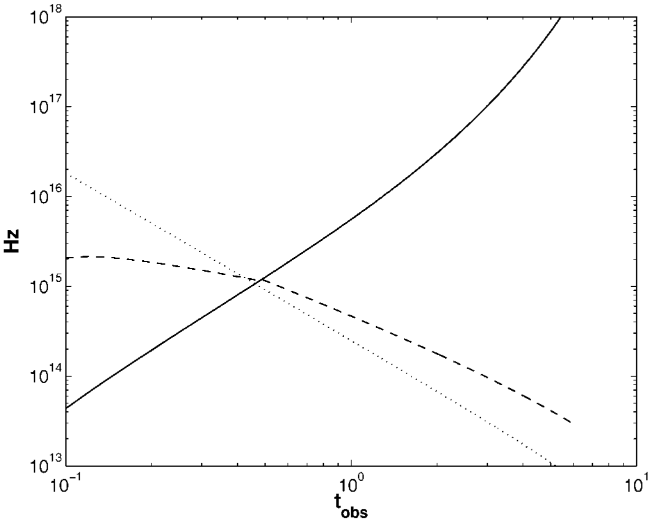

FIG. 1.—Radiation frequencies involved in an i-shell interacting with the trail of slow n-shells as a function of observer time. The physical parameters are taken as $M_{\rm ion} = 2M_n^0 = 5.6 \times 10^{26}$ g, which corresponds to a luminosity $L = 10^{52}$ ergs s^{-1} and $\delta t = 10^{-2}(1+z)$ s, $\Gamma_m = 200$, $\Gamma_{n,s} = 30$, $\epsilon_e = 0.3$, $\epsilon_B = 0.01$, and $z = 1$ ($D_L = 2.2 \times 10^{28}$ cm). The solid line, dashed line, and dotted line represent ν_c (the cooling frequency), ν_a (the synchrotron self-absorption frequency), and ν_m (the typical synchrotron frequency), respectively. The start point has been chosen to be $R = 10^{14}$ cm and the corresponding start time $t_{\rm obs,\,beg} = 0.04(1+z)$ s. The end point has been chosen as 2.5×10^{15} cm $\simeq 3R_{\beta,\,s}$ and the corresponding end time $t_{\rm obs,\,end} \simeq 3(1+z)$ s.

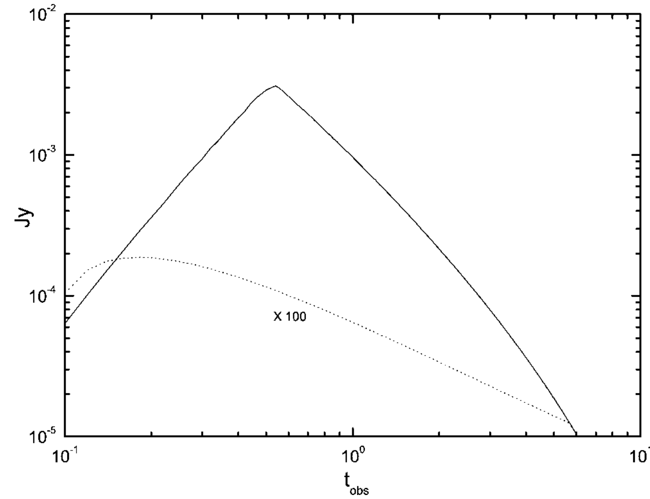

FIG. 2.—Synchrotron radiation powered by an i-shell interacting with the trail of slow n-shells as a function of observer time. The parameters are the same as those taken in Fig. 1. The solid line and dotted line represent $\nu_{\rm obs} = 10^{15}$ Hz and 5 keV, respectively. For clarity, the value of the dotted line has been multiplied by a factor of 100. Please note that what we observed is the emission powered by a series (several thousand) of i-shells interacting with the slow neutrons' trail, rather than just by one. In the simplest model proposed here, about 300 sample light curves overlap; each lags with $\delta t = 10^{-2}(1+z)$ s. The resulting net observable fluxes at 10^{15} Hz and 5 keV are about 0.11 Jy and 1.4×10^{-9} ergs cm^{-2} s^{-1}, respectively.

In the case of slow cooling,

$$F_\nu \approx F_{\rm max} \begin{cases} (\nu_m/\nu_a)^{(p'+4)/2}(\nu/\nu_m)^2, & \nu < \nu_m, \\ (\nu_a/\nu_m)^{-[(p'-1)/2]}(\nu/\nu_a)^{5/2}, & \nu_m < \nu < \nu_a, \\ (\nu/\nu_m)^{-[(p'-1)/2]}, & \nu_a < \nu < \nu_c, \\ (\nu_c/\nu_m)^{-[(p'-1)/2]}(\nu/\nu_c)^{-(p'/2)}, & \nu > \nu_c. \end{cases} \quad (5)$$

Here $F_{\rm max} = \{[3\sqrt{3}\Phi_{p'}(1+z)N_e m_e c^2 \sigma_{\rm T}]/32\pi^2 e D_L^2\}\gamma B$ approximately; $\Phi_{p'}$ is a function of p' (for $p' \sim 2.3$, $\Phi_{p'} \simeq 0.6$), N_e is the number of electrons involved in the emission, and D_L is the luminosity distance (Wijers & Galama 1999).

The upcoming satellite *Swift* will carry three telescopes:[4] the Burst Alert Telescope, the X-ray Telescope (XRT), and the Ultraviolet and Optical Telescope (UVOT). The energy range of XRT is 0.2–10 keV. UVOT covers 170–650 nm with six colors. Thus, in Figure 2 we calculate the emission at the observer frequency $\nu_{\rm obs,\,1} = 1.0 \times 10^{15}$ Hz and $\nu_{\rm obs,\,2} = 5$ keV.

The synchrotron radiation of an i-shell interacting with the trail as a function of the observer time is shown in Figure 2. What we observed is that the emission comes from a series (several thousands) of i-shells interacting with the trail of slow neutrons, rather than just from one. In the simplest model proposed here, ~3 s$(1+z)/\delta t = 300$, sample light curves overlap, each with a $\delta t/(1+z) = 10^{-2}$ s delay. The resulting net observable fluxes at 10^{15} Hz and 5 keV are about 0.11 Jy and 1.4×10^{-9} ergs cm^{-2} s^{-1}, respectively. The signature of 5 keV emission is only marginal, since the typical X-ray component during many GRBs is strong, too. Therefore we do not discuss it any further. The sensitivity of UVOT is about the 19th magnitude in a 10 s exposure. The spacecraft's time-to-target is about 20–70 s; in principle, part of, if not all, the emission predicted here could be detected in the near future. However, we need to investigate whether some other emissions during the prompt gamma-ray emission phase could dominate over the emissions predicted here. Recently, it has been suggested that the relativistic e^-e^+ pair generated in the internal shocks phase can power a UV flash of ~13th magnitude as well (Fan & Wei 2004). However, the actual value of that emission is proportional to $\Gamma_m^4[\delta t/(1+z)]^{5/2}$, and in that work the fiducial values for these parameters are taken as 300 and $0.1(1+z)$ s, respectively. If $\delta t \sim 0.01(1+z)$ s or smaller, as taken in this work, the UV flash predicted in Fan & Wei (2004) will be much weaker ($\lesssim$18th magnitude) unless Γ_m is much larger than 300. Thus the UV emission predicted in this work can be detected independently.

3. DISCUSSION

In the standard baryonic internal shocks model for GRBs (Paczyński & Xu 1994; Rees & Mészáros 1994), the prompt gamma-ray emission is powered by the interaction between ion shells with variable LFs. If these shells are neutron-rich, the neutron component coupled with the "fast ions" is accelerated to a larger bulk LF (approximately several hundred), i.e., the fast neutron component, which is the focus of many publications (e.g., PD02; B03). However, the neutron component coupled with the "slow ions" can be accelerated only to a moderate bulk LF of approximately tens, for which the typical β-decay radius ~10^{15} cm is significantly smaller than that of the fast neutrons. As long as the duration of GRBs is long enough, the earlier n-shells will be swept by the much later i-shells successively until the radius $\simeq R_{\beta,\,s}$, where the slow neutrons have decayed significantly. Consequently, the interaction may power observable emission.

In this Letter, with an extremely simplified model to describe the later but faster i-shells interacting with the much earlier but slow, decaying n-shells, we have shown that there comes a ~12th magnitude UV flash at a later stage of long GRBs. That emission is bright enough to be detected by the upcoming satellite *Swift* in the near future. The emission predicted here

[4] See http://swift.gsfc.nasa.gov/swift/about_swift.

is independent of the poorly known medium distribution around the progenitor of GRBs, as long as it is not very dense; it is also independent of some other physical processes, such as the e^-e^+ pair emission (Fan & Wei 2004), the possible reverse shock emission (as usual, if we assume that the number density of the ISM is about 1 cm^{-3}, $R_{\beta,s}$ is much smaller than the deceleration radius $\sim 10^{17}$ cm, at which about half of the kinetic energy of the ejecta has been converted into the thermal energy of the shocked ISM, for neutron-free ejecta), and so on.

The resulting net light curve in this work first increases rapidly. Then there comes a flat lasting $\sim T_{90}$, the duration of corresponding GRBs. Finally, the light curve drops sharply, when the observed emission is contributed mainly by the "equal-arriving surface" effect (e.g., Kumar & Panaitescu 2000; Fan et al. 2004), if other emission such as the reverse shock emission has not been taken into account. It should be noted that the model used here is a great simplification of the real situation, in which both the ion and neutron shells are moving with variable LFs, and hence it is natural to expect that the corresponding emission is variable with time as well. However, to simulate such complicated processes is far beyond the scope of this Letter. Nonetheless, the actual flux may not be far dimmer than our prediction since on average, the LFs of the slow n-shells and the i-shells are significantly different, but their masses are comparable. Thus their interaction can power a bright UV flash in the range $\sim 10^{13}$–10^{15} cm.

Y. Z. F. thanks T. Lu and Z. Li for their long-term encouragement on the subject of neutron-fed GRBs. We also thank the anonymous referee for her/his constructive comments. This work is supported by the National Natural Science Foundation (grants 10225314 and 10233010) and the National 973 Project on Fundamental Researches of China (NKBRSF G19990754). This work is in memory of Changlin Zhang (Chang'an University, China), Y. Z. F.'s university physics teacher, who passed away on 2004 September 6.

REFERENCES

Bahcall, J. N., & Mészáros, P. 2000, Phys. Rev. Lett., 85, 1362 (BM00)
Beloborodov, A. M. 2003a, ApJ, 588, 931
——. 2003b, ApJ, 585, L19 (B03)
Derishev, D. E., Kocharovsky, V. V., & Kocharovsky, Vl. V. 1999a, A&A, 345, L51
——. 1999b, ApJ, 521, 640
Fan, Y. Z., & Wei, D. M. 2004, MNRAS, 351, 292
Fan, Y. Z., Wei, D. M., & Wang, C. F. 2004, A&A, 424, 477
Fuller, G. M., Pruet, J., & Abazajian, K. 2000, Phys. Rev. Lett., 85, 2673
Guetta, D., Spada, M., & Waxman, E. 2001, ApJ, 557, 399
Kumar, P., & Panaitescu, A. 2000, ApJ, 541, L9
Mészáros, P., & Rees, M. J. 2000, ApJ, 541, L5
Paczyński, B., & Xu, G. H. 1994, ApJ, 427, 708
Panaitescu, A., & Kumar, P. 2002, ApJ, 571, 779
Piran, T. 1999, Phys. Rep., 314, 575 (P99)
Pruet, J., & Dalal, N. 2002, ApJ, 573, 770 (PD02)
Rees, M. J., & Mészáros, P. 1994, ApJ, 430, L93
Rossi, E. M., Beloborodov, A. M., & Rees, M. J. 2004, in Proc. Santa Fe GRB Conf., in press (astro-ph/0401355)
Sari, R., & Esin, A. A. 2001, ApJ, 548, 787
Wei, D. M., & Lu, T. 1998, ApJ, 505, 252
——. 2000, A&A, 360, L13
Wijers, R. A. M. J., & Galama, T. J. 1999, ApJ, 523, 177
Wu, X. F., Dai, Z. G., Huang, Y. F., & Lu, T. 2003, MNRAS, 342, 1131
Zhang, B., & Mészáros, P. 2004, Int. J. Mod. Phys., 19, 2385